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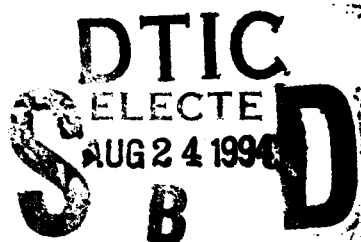**ARL**

Electronic and Fiber-Optic Applications in Pulsed Power Networks

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G. L. Katulka
S. Fortier

ARL-TR-404   May 1994

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REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1994	Final, January 1992–May 1993

4. TITLE AND SUBTITLE

Electronic and Fiber-Optic Applications in Pulsed Power Networks

5. FUNDING NUMBERS

4G031-315-R3-0001

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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ATTN: AMSRL-WT-PA
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-OP-AP-L
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

ARL-TR-404

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is ulimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The electrothermal-chemical (ETC) gun program at Aberdeen Proving Ground, MD, utilizes pulse-forming networks (PFN) to deliver electrical energy at specific energy profiles. This energy, when injected through a "capillary" chamber as a superheated jet, causes the combustion of propellants or working fluids. The possibility of attaining a greater pressure gain by delay-triggering the plasma injection from the conventional electric match propellant ignition (pressure raise), using an electronic voltage/pressure sensor and time delay generator, is discussed. The high electrical energy level involved in these PFN operations requires the use of a fiber-optic control system, which is also discussed.

14. SUBJECT TERMS

fiber optics, pulse-forming networks, firing circuits

15. NUMBER OF PAGES

31

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

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ACKNOWLEDGMENTS

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1. INTRODUCTION

The U.S Army Research Laboratory (ARL), Aberdeen Proving Ground, MD, is conducting investigations into the effects of high-energy plasma injection (Electrothermal-Chemical [ETC] Gun Program) to augment and control the combustion of propellants and working fluids. A closed chamber vessel is utilized to investigate the propellant combustion. Ignition is caused by an electric match (conventional ignition) or by electrical energy (plasma injection), which may also augment the propellant energy. The electrical energy is supplied by capacitor banks and pulse-forming networks (PFN). The propellant ignition can also be accomplished by the combination of a conventional ignition followed by the discharge of electrical energy. The electrical energy is injected into the closed bomb through an insulated electrode whose tip is connected to a grounded "erosion nozzle" by a nickel wire (Fortier et al. 1993). The disintegration of this thin wire, caused by the high-energy input, and the subsequent oblation of a thin polyethylene tubing or "capillary" (plasma capillary chamber), which holds the nickel wire in place inside an insulated E-glass fiber cylinder (80% glass continuous roving spool and 20% epoxy), creates a superheated jet which vents into the combustion chamber. This jet (plasma) reacts with the propellant, or working fluid, causing its combustion. The question of pressure gain potential obtained by the conventional (electric match) propellant ignition, followed by the plasma injection process, is of interest. However, in order to investigate this process, a method for delaying the trigger of the electrical (PFN)·discharge had to be developed. This report discusses the details of the implementation of the delay circuit.

The design of a fiber optic circuit to control high-voltage relays for the purpose of charging and discharging the PFNs is also discussed. This circuit employs normally "closed" relays that force the dissipation of the stored capacitive energy to ground. When the relay's status is "open," the PFN is enabled for charging.

2. BACKGROUND

The sequence of the plasma-augmented combustion first begins with the conventional ignition of the propellant in the 45-cm^3 vessel's propellant combustion chamber. It ends up with the electrical energy being injected in the 5-cm^3 plasma capillary chamber (see Figure 1) as the plasma initiated by the PFN discharge transfers the energy to the already ignited propellant during its later portion of pressurization. An amplified pressure transducer signal is used to enable a voltage detector circuit to trigger a time delay generator which subsequently triggers the PFN ignition switch at very early stages of the propellant

ANODE —
PLASMA CAPILLARY —
CATHODE —
PROPELLANT CHAMBER —
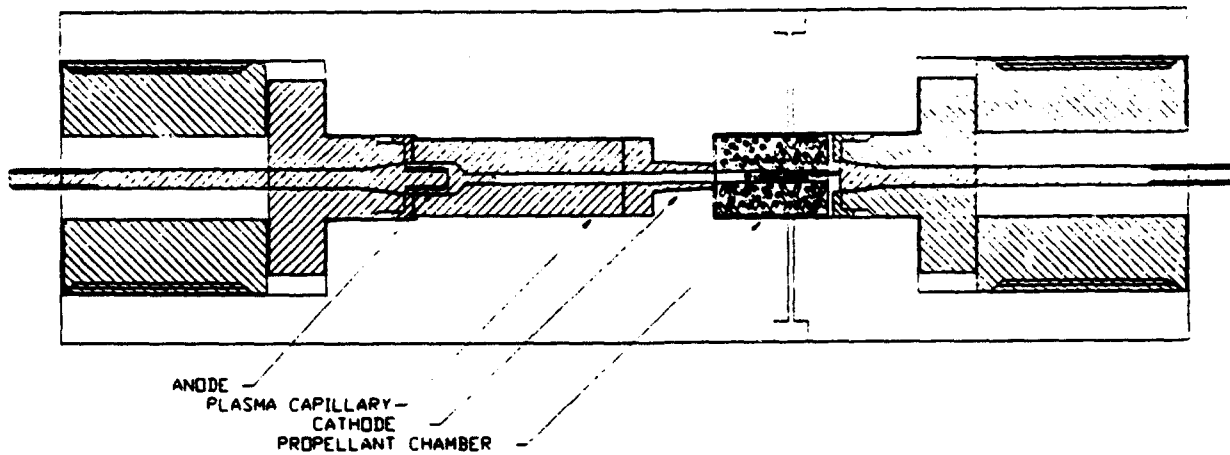
Figure 1. 50-cm^3 closed chamber vessel.

pressure profile. The voltage detector allows the triggering of the time delay generator, and subsequently, the introduction of variable time delays, making possible the determination of the best time frame for the plasma injection and studies to characterize electrical energy optimization.

The closed chamber ETC firing circuit was seen to introduce an inherent 100-μs delay between its triggering time and the time that the PFN discharges (ignitron switching) into the closed chamber. Also, a 50-μs delay was observed (Oberle and Katulka 1993) between the time that plasma was, injected into the vessel and the time that the related pressure was detected inside the vessel (Figure 2). Therefore, these delays had to be taken into account if a preset time delay was added between the time of the conventional ignition process and the time of injection of the electrically generated plasma into the propellant. The total time delay had to allow the plasma energy to be added prior to the point of mismatch between assumed propellant geometry and actual geometry. This will often occur after propellant grain slivering (Oberle et al. 1993). Slivering occurs when the propellant web burns through and the calculated surface area is no longer reliable.

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CURRENT (AMPS)

1.5E+4

1.25E+4

1.0E+4

7500.0

5000.0

2500.0

0.0

-2500.0

PRESSURE GAGE OUTPUT (VOLTS)

0.6

0.5

0.4

0.3

0.2

0.1

0.0

-0.1

——— PFN Current
······ Pressure Gage Output

500.0uS   1.0mS   1.5mS

TIME

Figure 2. PFN current input vs. closed chamber pressure output.

3. EXPERIMENTAL DETAILS AND APPARATUS
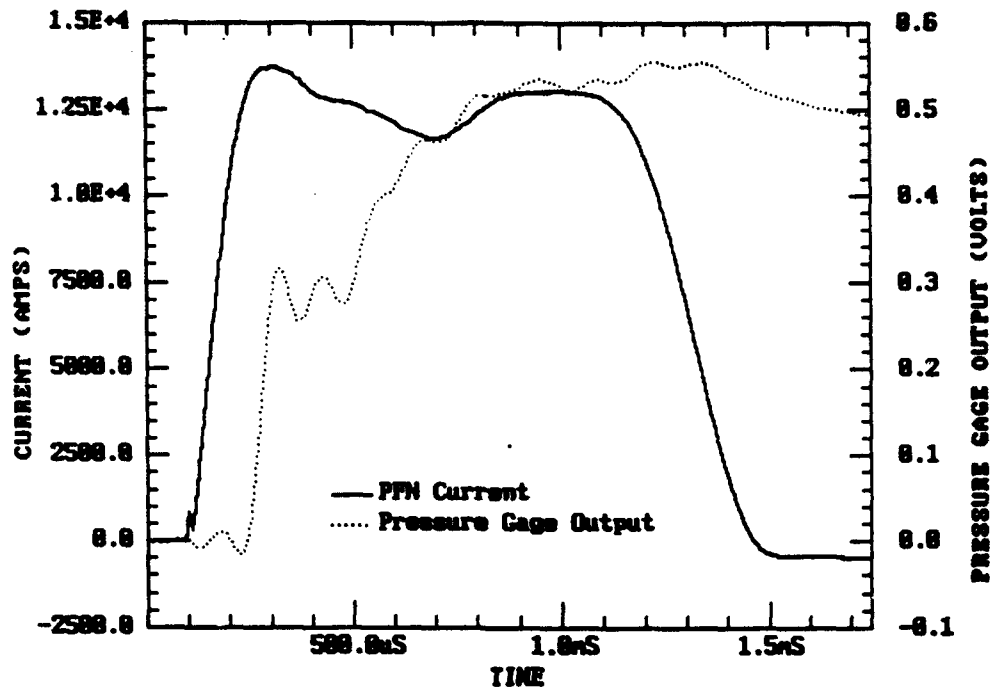
Data acquisition for voltage and di/dt PFN output usually requires a faster sampling rate than the one used for pressure (PT traces) as the initial transfer of the electrical energy from the PFN into the closed chamber occurs at a much faster rate than the propellant pressure rises (i.e., for M5, typically 800 μs for electrical energy up to 90% rise and 1.8 ms for 90% pressure rise). As a result, a substantial difference between sampling rates during ETC closed chamber firings (i.e., 0.5 μs/pt) for voltage and di/dt data acquisition vs. those used (i.e., 5 μs/pt or 10 μs/pt) for pressure, made difficult the determination of the precise moment the chamber pressure began to rise with respect to the electrical energy input. For that purpose, on 5–8 April 1993 several ETC firings were performed with an empty chamber (no propellant) using the same 0.5 μs/pt for both PT and electrical data. These tests utilized an E-glass liner, erosion nozzle, and nickel wire configuration at 15 KJ (3 KV), which simulated the experimental configuration used for typical ETC firings (Fortier et al. 1993).

For all test cases, it was observed that the pressure trace started to rise after the current peaked and reached its maximum value when the electrical energy input was completed. The current pulse required

3

an average of 200 μs from initiation time to peak, and the delay for the rise of the pressure pulse for all firings was about 50 μs from the current initiation time. Therefore, the transfer of energy from the PFN to the combustion chamber showed an average delay of 250 μs. This transfer of energy was completed after 1.2 ms, which was in agreement with the analytically calculated current profile for this 300-KJ PFN (see Figure 3).

174 Temperature= 27
T in M
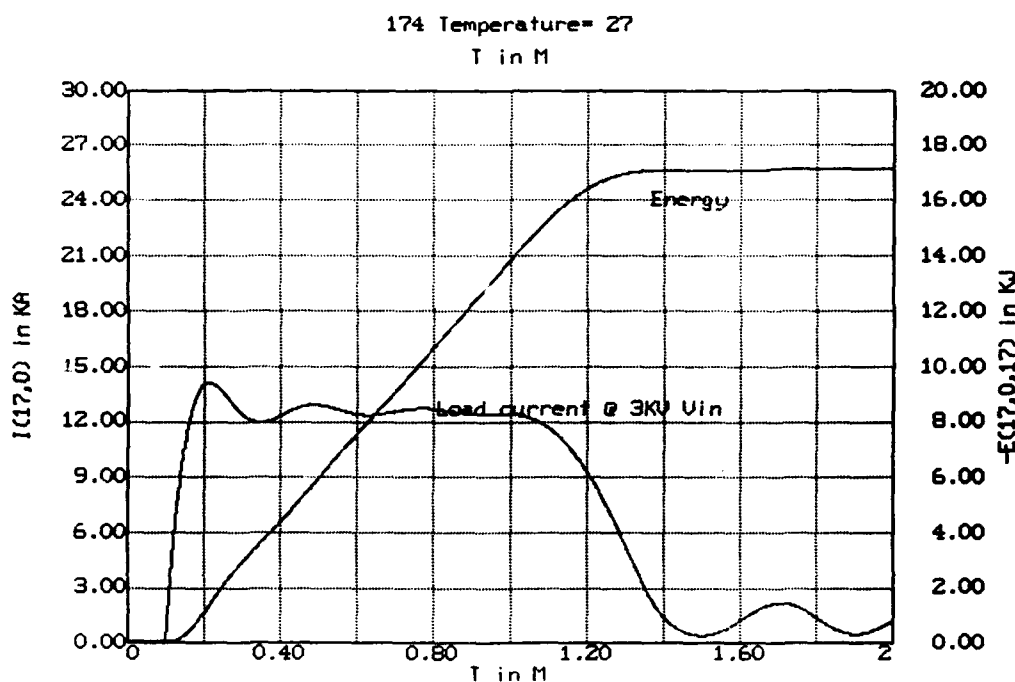
Figure 3. Analytical (Microcap III) current and energy profiles of 300 KJ PFN.

Before a propellant charge could be initiated conventionally and electrical energy added at a latter time, it was essential that the triggering delay associated with the electrical energy input process was minimized, so that the available time frame for plasma injection was maximized. The 250-μs time delay between the ignitron triggering and the delivery of the electrical energy was found to include an undesirable 100-μs delay introduced by the ignitron impulse firing circuit. This delay was eliminated by triggering the ignitron from a piezo-electric pressure transducer via fiber-optic link, utilizing the amplifying voltage detector circuit shown in Figure 4.

Signals from a Kistler quartz pressure transducer (model 607C4) are processed by a Kistler Dual Mode Voltage Charge Amplifier (model 5004). A fiber-optic link, consisting of a transmitter (Dymec

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Figure 4. **PFN triggering system layout.**

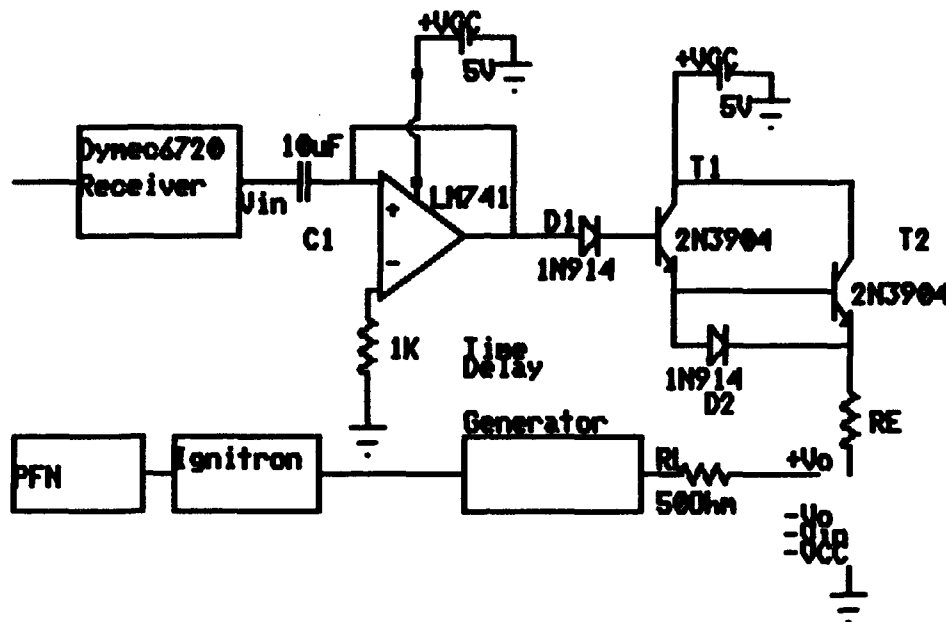model 6723) and a receiver (Dymec model 6722), transfers this signal from the range to the amplifying voltage detector (see Figure 5). The previous 250-μs time delay was reduced to 150 μs, providing a wider time frame for the injected plasma to interact with the burning propellant and affect its burning rate. The amplifying voltage detector has a delay of less than 1 μs and outputs over 3 V with a minimal input signal of 400 mV, which corresponds roughly to 1/20 of the maximum pressure rise (8.05 V calibration output or 50,000 psi maximum). The final pressure rise should then not exceed 20 times this minimum pressure trigger level.

The first approach was to utilize an existing "impulse bomb igniter firing circuit" to energize the electric match. This circuit is manually triggered and has enough power output to provide input to both the electric match firing circuit and to a parallel ignitron circuit. By adding a time delay generator in series with this ignitron input circuit, the PFN could be fired with a selected time delay when the manually triggered impulse had ignited the electric match. This setup required that the magnitude of each propellant ignition time delay involved (different from shot to shot) had to be determined in advance. Without knowing this delay, there would be no means of controlling the plasma injection, which is critical in understanding the effects of the plasma energy on the later portions of the pressure rise. However, if the

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PFN is triggered from the pressure rise due to the propellant ignition, then the PFN can be triggered at a given voltage signal (approximately 400 mV with the addition of the voltage detector circuit) which corresponds to a known time during the pressure rise. Triggering at that given voltage ensures repeatability from shot to shot.

The closed pressure vessel (closed bomb) shown in Figure 1 consists of a plasma capillary chamber (ETC injection side) and a 45-cm^3 propellant combustion chamber. The combustion chamber pressure rise is detected by the piezo-electric pressure transducer (Kistler 607C4) sent to a charge amplifier (Kistler 5004 Dual Mode Charge Amplifier) and transmitted by fiber optic link (Dymec 6720 Transmitter Receiver pair) into the amplifying voltage detector circuit. This circuit initiates a time delay generator which triggers the PFN ignitron switch (see Figure 5), causing the plasma to be injected into the combustion chamber of the vessel (see Figure 1). The time delay generator consists of a power supply, a trigger channel, and delay panels which allow different delays—from microseconds to milliseconds (models 40150-J, 40150-I, 40150-G, and 40150-C). This delay generator has a maximum input of 10 V at 200 mA and outputs two signals, one directly to the PFN ignition (500-V maximum) and a synchronous (10-V maximum) output to enable connections to the other panels or other instrumentation, such as a digital oscilloscope, for triggering purposes.
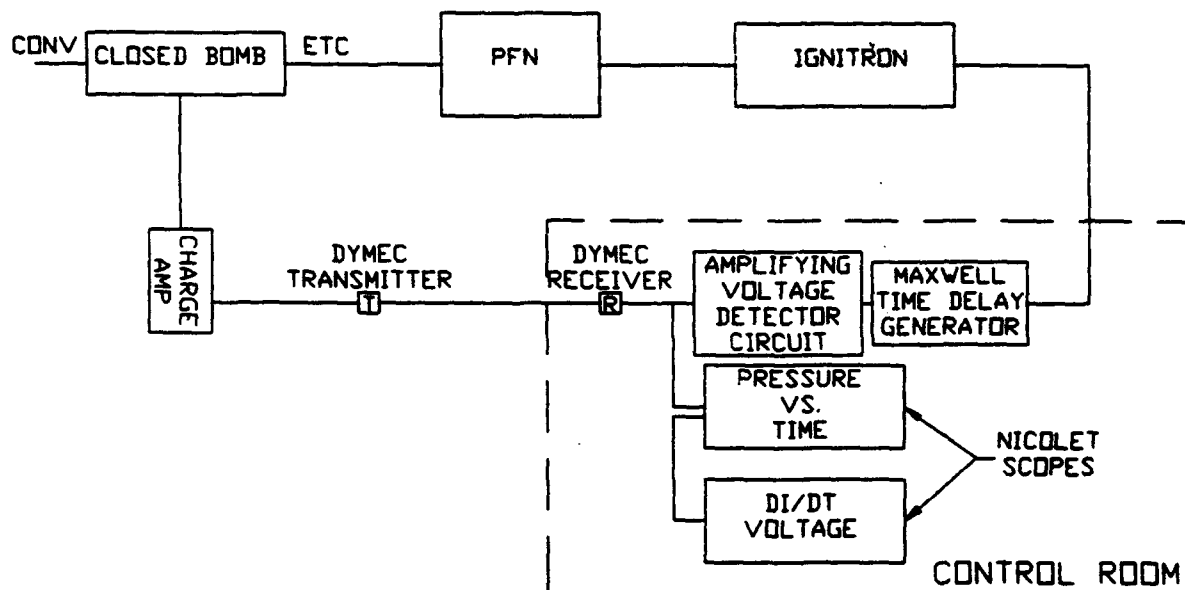

Figure 5. Acquisition system layout.

In normal closed chamber tests, two pressure gauges monitor the pressure rise in the combustion chamber—one mounted at the muzzle end of the chamber and a second mounted in the combustion chamber wall. For these tests, however, the electric match, which provides the conventional ignition for the propellant, is mounted at the end of a steel electrode to prevent extrusion, in place of the muzzle end mounted gauge. Only the side-mounted pressure gauge is used, and, as mentioned previously, its pressure signal is sent via the microdot wiring to a charge amplifier. This charge amplifier is connected to the transmitter/receiver fiber-optic system which delivers the signal to be recorded into a 4094 Nicolet oscilloscope. This amplifier is also connected to the voltage detector circuit and time delay generator which in turn triggers the ignition (PFN mercury switch) (Figure 5).

4. CIRCUIT

The ideal arrangement would have the time delay generator triggered directly from the Dymec fiber-optic link output, which in turn would trigger the ignition and fire the PFN. For the purpose of determining the amplitude of the required triggering signal, different voltages were tested using the charge-amplifier and fiber-optic link. In these tests, the Dymec fiber-optic link had to output a 3-V minimum amplitude signal in order to trigger the time delay generator. This would account for over one-third of the total pressure rise, allowing no room for possible time delays or effective interactions of the plasma with the burning propellant. If, in turn, the gain in the charge amplifier was increased so that a 3-V minimum output signal was obtained with a smaller input signal, then the resulting calibration constant was too large and the pressure data obtained suffered undesired "clipping."

The added circuit detects the pressure rise at a lower voltage amplitude and amplifies the signal, providing an adequate input that triggers the delay generator while allowing the charge amplifier to be set at the proper calibration ratio. The minimum voltage required for triggering was shown to be about 400 mV, roughly eight times less than before.

An alternating current (AC) coupling capacitor (C1) allows the pressure pulse into the inverting input of an LM741 operational amplifier. The LM741 requires typically low supply current and, as connected, offers a low input impedance. The capacitance chosen for C1 is 10 µF, and since its reactance is very small compared to the 741 input impedance, it is seen as a short circuit by the AC input signal (see Figure 4).

The amplified signal is sent into a second stage across a 1N914 diode (D1) to avoid any feedback into the first stage. The LM741 sets the current (Ib) at the base of the first NPN transistor so that both 2N3904 transistors become biased in their operating regions. These 3904 NPN transistors are connected to form a CC - CC "Darlington pair" (Ryder 1976). This connection makes both transistors work as a single unit, but with a total current gain of at least the product of each of the direct current (DC) collector-base current gains (hFE) of each NPN transistors (T1 and T2) (see Figure 4). The net effect of the Darlington circuit is to raise the gain of an individual transistor by a power of two, assuming approximately equal transistor gain (see Appendix A).

The obtained output was over 4 V with 80 mA into 50 Ωs. The ignition triggered each time the simulated "calibration" signal (with PFN discharged) was produced at 400 mV (minimum). Most importantly, the circuit functioned properly during conventionally initiated firings and triggered the delay generator which in turn discharged the PFN at desired preset delays. Figures 6a–c document a 400-mV input signal into the voltage detector, its 3.316-V output which causes the triggering of the time delay generator, and the 52.44-V generator output that triggers the ignition switch. The circuit behavior was simulated through Microcap III. Two switches closed from 5 µs to 6 µs to simulate a pulse or transient similar to the one caused by the calibration signal used to test the actual circuit. The results are shown in Figures 7a–c (see also Appendix A).

5. FIBER-OPTIC CIRCUIT

ARL's Weapons Technology Directorate (WTD) has various capacitor-based pulsed power facilities. Due to the large electrical energy involved, usually on the order of hundreds of kilojoules, their use requires that the charging and grounding of the capacitor banks be performed cautiously and safely. Because of the excellent isolation provided by fiber-optic transmission/receiver links, a Hewlett-Packard fiber-optic transmitter (control room) and receiver (range) models HFBR 1524/2524 were used to send a DC control signal from the control room to PFN relays.

The Hewlett-Packard fiber-optic transmitter TX1524 sends a DC control signal to a hybrid SSRT 120D10, 120-V AC, 3- to 32-V DC relay, via its RX2524 receiver. This relay, in turn, controls the AC voltage input of the high-voltage relays (Ross Engineering model E25-NC-25-2-0). By closing or opening these relays, the capacitor banks are grounded or lifted from ground (via a 5% $CuSO_4$ water solution "dump" resistors), enabling the PFN to be energized.
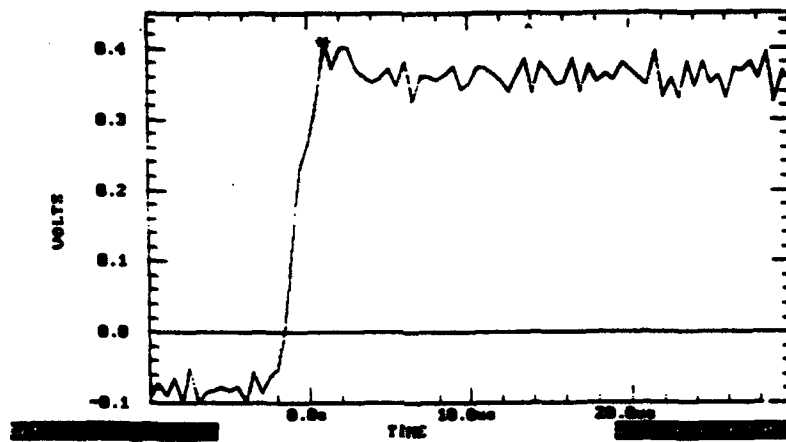
Figure 6a. 400-mV minimum (Dymec) input signal into amplifying voltage detector.
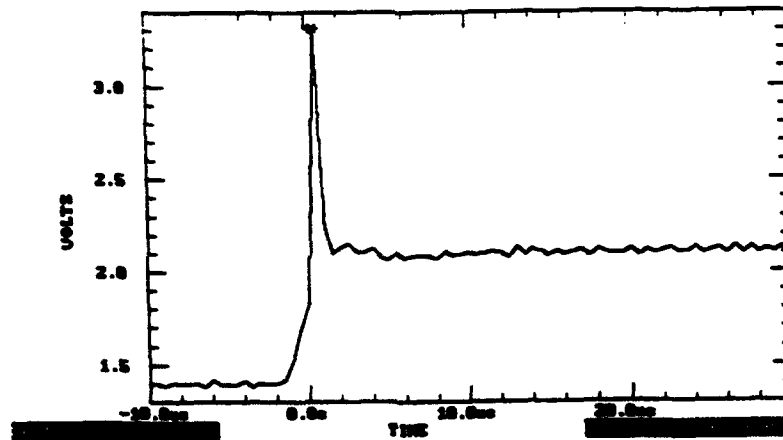

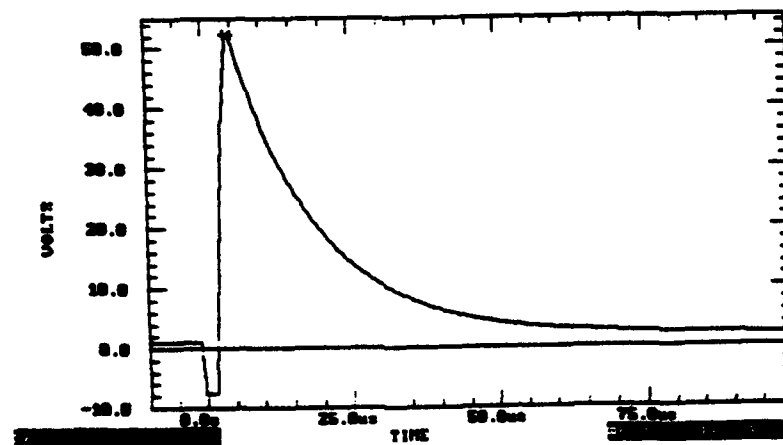Figure 6b. Amplifying voltage detector output into time delay generator.

Figure 6c. Time delay generator transformer coupled output into ignition switch.
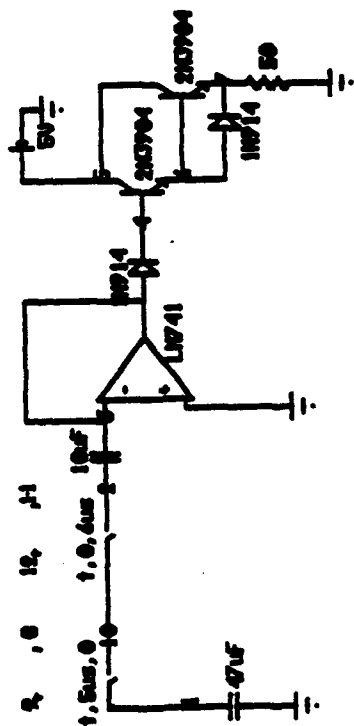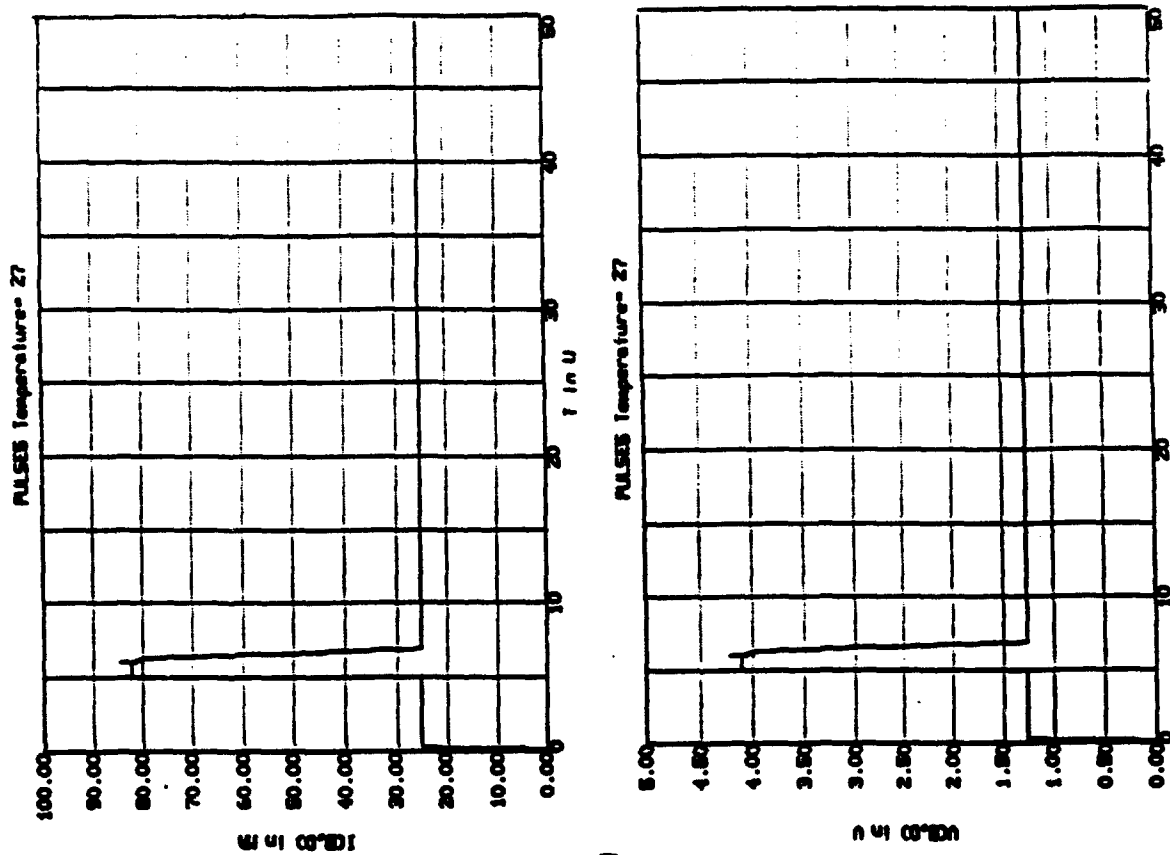
Figure 7a. Amplifying voltage detector voltage and current outputs across time delay generator 50-Ω input impedance.

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Figure 7b. Amplifying voltage detector voltage and current outputs across time delay generator 50-Ω input impedance (D2 diode replaced by 50-Ω resistor).
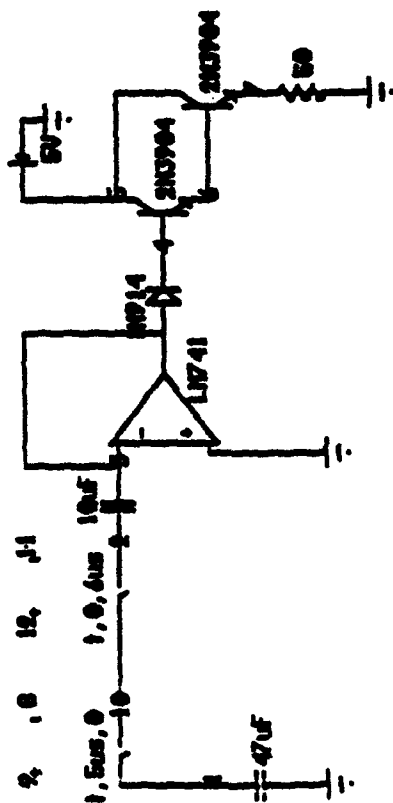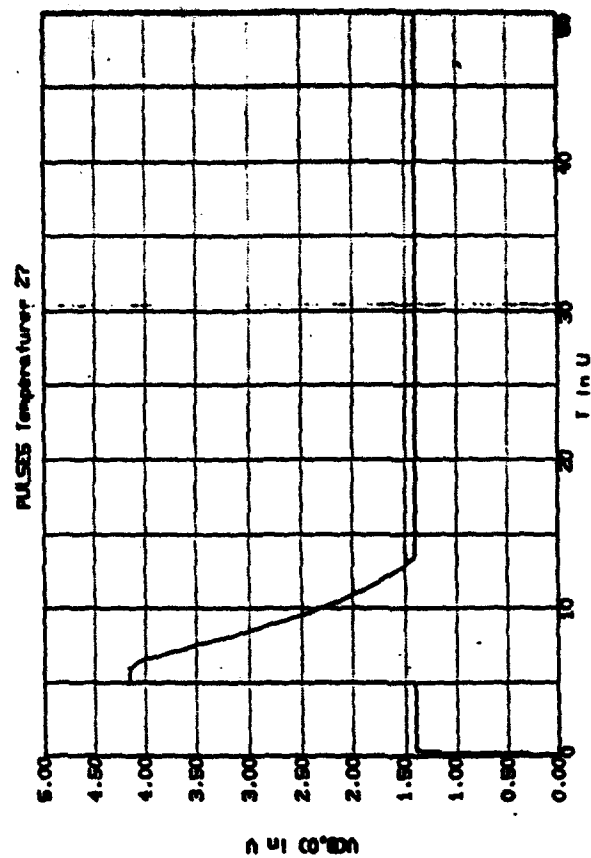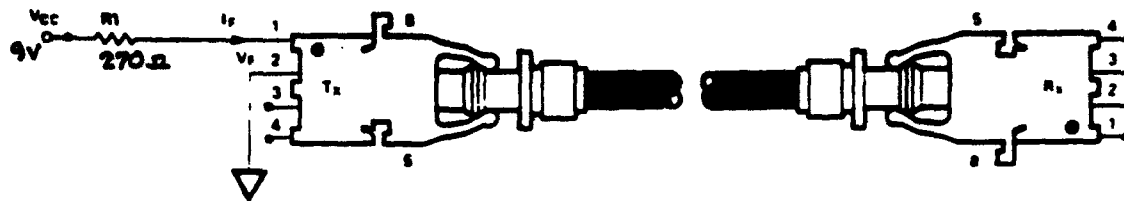
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Figure 7c. Amplifying voltage detector voltage and current outputs across time delay generator 50-Ω input impedance. (D2 diode replaced by short).

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The TX1524 transmitter is powered by two 9-V batteries connected in parallel. A 270-Ω resistor is used at pin No. 1 (Figure 8) to set an input current to the light-emitting diode (LED) below its 750-mA maximum rating. Pin No. 2 is connected to ground, and pin Nos. 3 and 4 are not used. The transmitted signal activates a photodiode located in the RX2524 receiver, whose output is amplified and sent into a Schottky transistor. The receiver has a provision to "pull up" a high output through a 1-kΩ "pull up" resistor on pin No. 4. Pin No. 1 is the output and pin Nos. 3 and 2 are the VCC (+5-V DC applied voltage source) and ground connections, respectively. A secondary circuit (see Appendix B), which consists of an NPN transistor, Nor gates, and LM741 op-amps, correlates the transmitter amplified signal into the SSRT hybrid and high-voltage relays matching an "ON" status with an "OPEN" relay mode and an "OFF" status with a "CLOSED" one. This secondary circuit also ensures that the high-voltage relays are set "ON" or "OPEN" only when the TX1524 transmitter is "ON." An uninterruptable power supply (UPS) is used inside the range because undesirable fluctuations in the AC could affect the DC output voltage level on the AC/DC converter that powers the RX1524 receiver and the secondary circuit, causing damaging high-voltage relay "chatter." A Microcap III simulation (see Appendix B) shows the output at the hybrid relay DC terminals.

6. SAFETY

The arrangement previously mentioned controls the high-voltage relay operation solely by the "ON" and "OFF" of the fiber-optic switch. The usage of the mentioned UPS ensures a stable +VCC of +5 V for the RX2524 receiver, avoiding the possibility of high-voltage relay "chattering" (Katulka et al. 1991; Eccleshall 1990). The 500-Ω resistor added across the DC side of the SSRT hybrid relay reduces its 5-kΩ input impedance and boosts the output current. This arrangement maximizes the voltage/current gain when the hybrid relay in "ON." The potential differences between these "HIGH" and "LOW" outputs easily control the SSRT (4-V DC maximum at 8 mA), providing a very reliable "CLOSED" or "OPEN" PFN relay mode. Two of the high-voltage PFN relays auxiliary outputs are connected each by a 1-kΩ resistor to 3-V DC red and green LEDs, respectively. These, in turn, are grounded by 470-Ω resistors.

At the range, an AC/DC converter solid-state power supply (Global series GHF 1-24) provides the +5-V DC for the +VCC of the RX2524 fiber-optic receiver, the 4001 "NOR" gate, and both LM741 op-mps. It also provides the AC needed for the high-voltage relay operation. If this AC/DC converter is "ON" and the fiber-optic link is set "OFF," the high voltage relays will close ("OFF" mode), and consequently, the green LEDs will be set "ON" (safe mode). If, however, the fiber optic-link is set
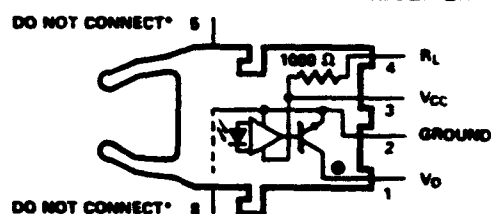
HFBR-152X/153X SERIES TRANSMITTERS

ANODE 1
CATHODE 2
N.C. 3
N.C. 4

DO NOT CONNECT* 8
DO NOT CONNECT* 5
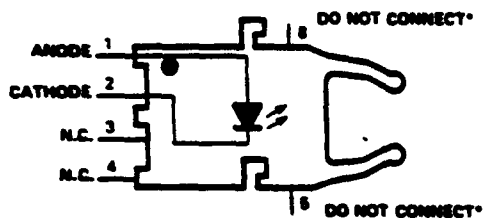
*SEE NOTE 7

HFBR-25X1/25X2/25X4 RECEIVER

DO NOT CONNECT* 5
DO NOT CONNECT* 8

1000 Ω
R_L 4
V_{CC} 3
GROUND 2
V_O 1

QUAD TWO-INPUT NOR GATE   4001

PIN CONNECTION

TOP VIEW
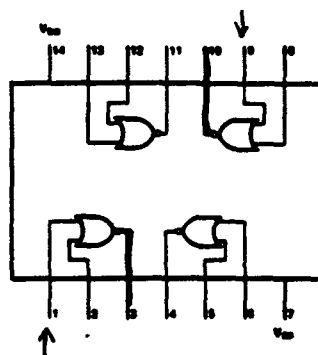
A	B	OUT
L	L	H
L	H	L
H	L	L
H	H	L

NOR Gate

TRUTH TABLE

Figure 8. Hewlett-Packard fiber-optic transmitter/receiver HFBR 1524/2524, 4001 NOR gate schematics, and truth table.

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"ON," the high-voltage relays will open ("ON" mode), and the red LEDs will be set "ON" (unsafe mode). If the AC/DC converter is "OFF," the "ON" and "OFF" of the fiber-optic signal has no control on the relays.

7. CONCLUSIONS

The Maxwell-ignition circuit allowed PFN triggering at very early stages of the conventional pressure rise, via the Kistler signal, and added the wanted delays on the plasma injection to the ETC part of the combustion cycle. The optoelectronic circuit has been operating as a remote control switch for two PFN facilities located at Bldg. 390, Ranges 161 and 174 (100 kJ and 150 kJ, respectively). It has been proven to be very reliable and has enhanced the safety in the operation of the capacitor banks involved.

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APPENDIX A:

AMPLIFYING VOLTAGE DETECTOR CIRCUIT

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The current Ie at the emitter of T1 equals

$$(1 + hFE[T1]) * Ib(T1) = Ib(T2),$$

which is the base current to T2, and being the current at the emitter of T2 equal to

$$(1 + hFE[T2]) * Ib(T2).$$

The current gain, $Ie(T2)/Ib(T1)$, is approximately equal to

$$hFE(T1)*hFE(T2).$$

The emitter of T1 connected to the base of T2 creates an "emitter feedback," which assures the circuit linearity. However, if the emitter of T1 and the emitter of the second transistor T2 are connected by a second 1N914 diode (D2), a faster turn "off" for T2 occurs (see Figures 6a and 6c), limiting the current leakage from T1 to the base of T2 because of the voltage drop across the diode D2, thus avoiding setting T2 into conduction with the leakage current. The input resistance into T1, without the second diode D2, would equal hFE(T1) multiplied by the input resistance into the base of T2, which equals

$$hFE(T2) * RL$$

and is substantially larger. Because D2 has a resistance RD2 of less than 100 Ωs, in parallel to the 50-Ω "load" resistance RL of the time delay generator, this results in a resistance equal or less than 50 Ω. The input resistance to T1 is then approximately equal to

$$hFE(T1) * 50$$

or less than 5 kΩ, and because the 741 op-amp has the inverted input connected to the output pin, its input resistance Zin is negligible (otherwise on the order of 10E+12 Ωs). So, as the 10-μF capacitor plus the 5 kΩ input impedance acts as a high-pass filter, the f3db break point equals

$$1/(2*pi*Zin*C),$$

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which is less than 1 kHz. Because of no emitter "feedback" due to the second diode D2, the circuit is no longer linear (see Figure 7a), producing a peak at its output as desired. Figure 7c shows the slower turn "off" of T2 when the emitter of T1 is connected directly to the base of T2. Figure 7b shows the behavior of the circuit when a resistor (50 Ω) comparable to the resistance of D2 connects T1 and T2 instead, decreasing the gain substantially.

APPENDIX B:

FIBER-OPTIC CONTROLLED SECONDARY CIRCUIT

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When the Schottky is "ON" (RX2524 "ON"), pin No. 1 is grounded by way of pin No. 2, which is connected to ground. When the Schottky is "OFF," it creates a high resistance between output pin Nos. 1 and 2 to ground. This fact is used (Figures B-1a and B-1b) to connect an NPN 2N3904 transistor in the following way: collector C to pin No. 4, base B to pin No. 1, and emitter E to ground, across a 1.5-MΩ resistor. Pin Nos. 4 and 1 have a 1-kΩ resistor across them, to set the right base current at VB, base to the NPN transistor, when the Schottky transistor is "OFF."

When the Schottky is "ON," the output CB taken from the base B of the NPN is low (as pin No. 1 is grounded through Schottky transistor to pin No. 2). But when the Schottky is "OFF," a base current is established through B, and the NPN is biased properly as pin No. 4 is "HIGH," and the transistor is then operating in its active region, creating a high output at VB. The output is taken from B, instead of E, because the emitter voltage VE is almost totally dependent of the +5-V DC. This voltage, for all purposes, would control the hybrid relay instead of the "ON," "OFF" from the fiber-optic link. Because a "HIGH" output at VB is obtained when the switch is "OFF" and a "LOW" output is similarly obtained when the switch is "ON," a "NOR" gate is used as a next step in the circuit, to make the "HIGH" output correspond to an "ON" switch and the "LOW" output to an "OFF" switch. The "NOR" gate "truth table" is shown in Figure 8. Only two "NOR" gates are used of the total four provided by the 4001 chip. Each has two inputs. By grounding one, as the table shows, its output can only be "HIGH" when the other input is also "LOW." Because further amplification is needed, as the hybrid SSRT relay requires 3-V DC input minimum, 2 op-amps are added to the circuit. The input to the "NOR" gates is by way of pins Nos. 1 and 9 and the outputs by pin Nos. 3 and 10. The output from pin No. 3 (NOR1) will be the input to a first LM741 op-amp, which will output the +VCC voltage to operate the second "NOR" gate (NOR2). Pin No. 10 will in turn provide the input to the second op-amp.

The Microcap III simulation in Figures B-1 through B-3 show the output at a 500-Ω resistor R1 (across a hybrid relay DC terminals) to be in agreement with the actual circuit. For purposes of simulating the action of the fiber-optic switch on the circuit, two switches are used to set a square pulse of a 30-μs length. The actual circuit has the second LM741 powered by the output of the first LM741, and the two "NOR" gates have the +5-V source as their +VCC source. As the Microcap III simulation does not provide an input port in the schematic for the op-amps +VCC, but it does for the "NOR" gates, the output of the first LM741 is shown connected to power the second "NOR" gate. The final result is the same, as the second LM741 actuates the high-voltage relays only when the fiber-optic signal has been processed through the first "NOR" gate, enabling the second "NOR" gate via the first LM741. Either way, these
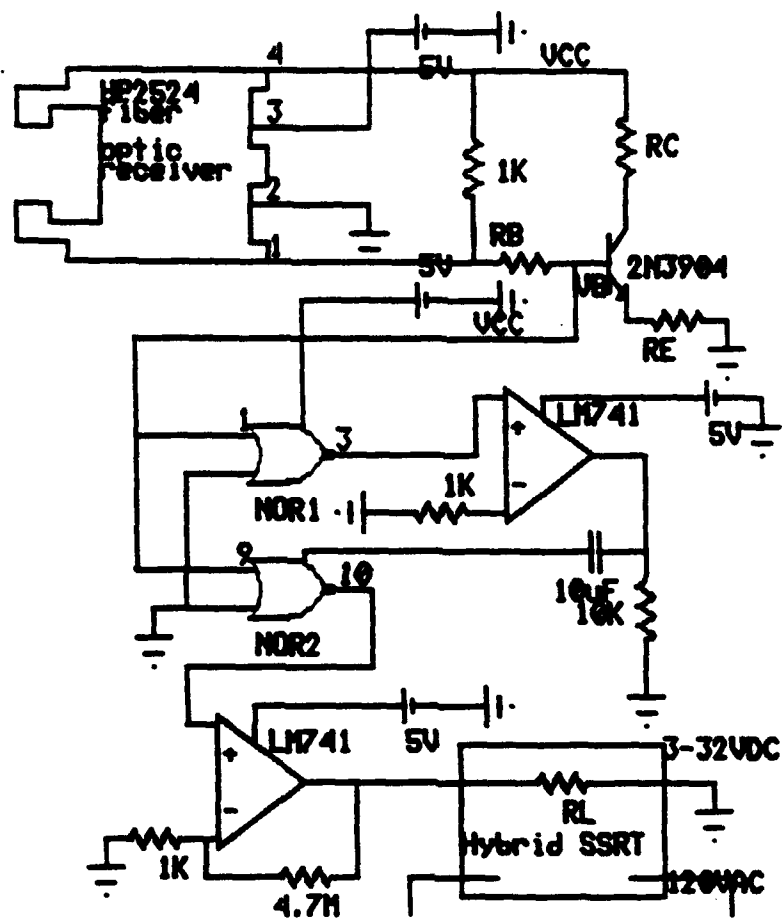
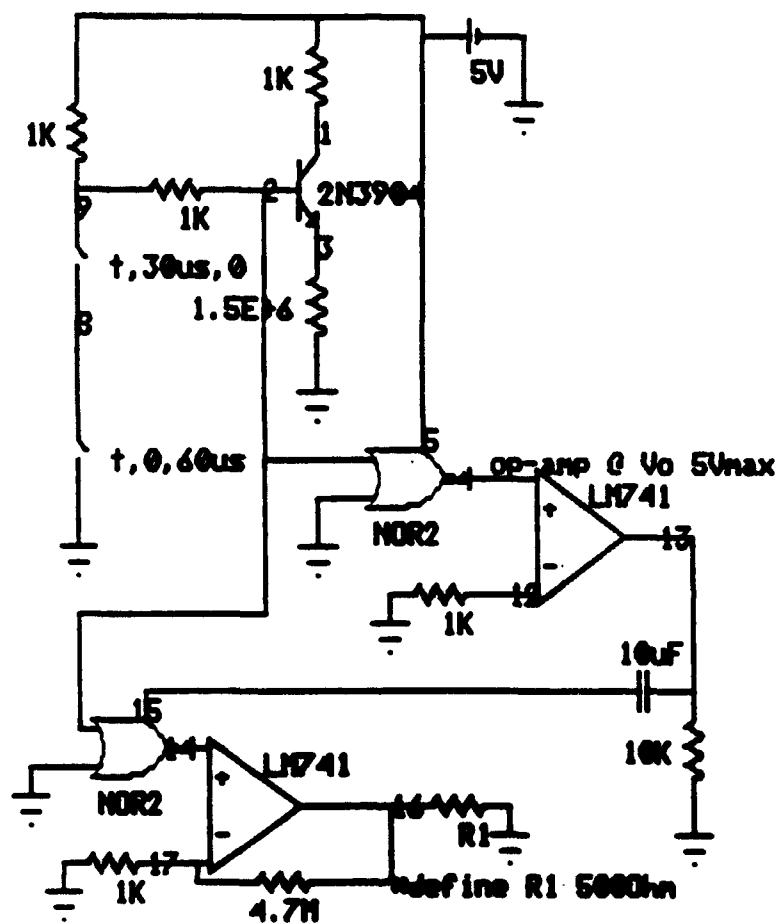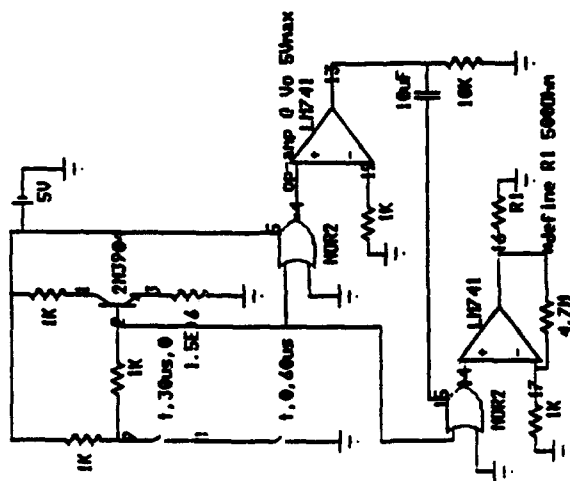Figure B-1. Fiber-optic and secondary circuit layout.

Figure B-2. <u>Secondary circuit schematics and Microcap III simulation.</u>

Figure B-3. Microcap III secondary circuit voltage and current simulation output at hybrid relay DC connector.

connections assure that the high-voltage relays can be set "ON" only when the fiber-optic signal has reached the RX2524 receiver. However, if undesired fluctuations offset the +5-V VCC while the fiber-optic switch is "ON," the high power relays will "chatter." This can be avoided by powering the AC/DC converter, which is the +5-V VCC source for the RX2524, through an UPS.

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